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Evaluation of Nitrate-Nitrogen Transport in a Potato–Barley Rotation

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ABSTRACT

Well water NO_3^-–N concentrations have been found to exceed 10 mg L^{-1} of NO_3^-–N for some areas of the San Luis Valley (SLV) of South-Central Colorado. The region's predominant soils are sandy soils, with a dominant potato (*Solanum tuberosum* L.) followed by malting barley (*Hordeum vulgare* L.) crop rotation. There is limited knowledge about how much NO_3^-–N is lost by leaching from these systems, and protocols need to be developed to evaluate the NO_3^-–N transport out of these coarse textured soils from these arid and semiarid irrigated cropping systems. Management information, N content at harvest, initial and final NO_3^-–N in the soil profile, and other supportive data were collected at 14 commercial fields and used as inputs for the Nitrate Leaching and Economic Analysis Package (NLEAP) model, version 1.20. NLEAP simulated available soil water for the root zone as well as the transport of NO_3^-–N in the soil profile, and can be used as part of the protocol to evaluate the NO_3^-–N transport of these systems. Best recommended practices in this region, such as application of N fertilizer rates on the basis of soil test analysis and split applications of N fertilizers, kept the net transport of NO_3^-–N out of the potato–barley systems to a minimum. Our approach of applying simulation models to assess management scenarios showed that barley served as a scavenger for the NO_3^-–N that was added with irrigation water and the residual soil nitrate from the potato growing period.

Contamination of drinking water by NO_3^-–N has been widely documented as a serious problem in many areas (Milburn et al., 1990; Follett et al., 1991; McCracken et al., 1994; Owens and Edwards, 1994). Drinking water supplies with NO_3^-–N concentrations higher than 10 mg L^{-1} of NO_3^-–N are considered unsafe for human consumption (USEPA, 1989). Well water NO_3^-–N concentrations exceeding 10 mg L^{-1} of NO_3^-–N with observations as high as 76 mg L^{-1} of NO_3^-–N occur in some areas of the SLV of south-central Colorado (Edelmann and Buckles, 1984; Austin, 1993; Eddy-Miller, 1993; Agro Engineering Inc. and Colorado State University, 1995). This high altitude desert valley has a mean elevation of 2341 m and 180 mm average precipitation (Edelmann and Buckles, 1984). Most soils are of a coarse sandy texture over a coarse-textured substratum (USDA-SCS, 1973; USDA-SCS, 1988) with a predominant crop rotation of potato followed by barley. This region produced 90% of the potato, 77% of the spring wheat (*Triticum aestivum*L.), 81% of the barley, 32% of the oat (*Avena sativa* L.) and 12% of the hay produced in the state of Colorado during 1996 (Colorado Department of Agriculture and USDA, 1997). During 1996, Colorado was the fifth highest producer of potato in the USA, so this region is also of high agricultural importance for the USA (USDA, 1997).

Since it is not possible to measure and quantify N losses in all field situations, simulation models are used to describe and evaluate the effect of general field conditions and management scenarios on N cycling. These mechanistic models are technology transfer tools capable of assessing management impacts of agricultural systems on soil NO_3^-–N available for leaching, NO_3^-–N leaching, N use efficiency (NUE), the net NO_3^-–N recovery from underground irrigation water, and nitrogen and water budgets. These models can be used to predict the NO_3^-–N dynamics, such as transformations and balance between the inputs and outputs and can evaluate the performance of a cropping system as a function of the interaction between management practices and the environment. The NLEAP model has been developed on these criteria and permits a rapid site-specific evaluation of best management practices (BMPs) for farmer's fields; for additional specific information see Shaffer et al. (1991).

Beckie et al. (1994) reported that NLEAP simulations of NO_3^-–N and water content in the rooting zone of wheat were similar to those simulated values from the Crop Estimation through Resource and Environment Synthesis (Godwing et al., 1984; Ritchie et al., 1985), the Erosion/Productivity Impact Calculator (Williams, 1982; Williams et al., 1984), and the Nitrogen, Tillage, and Crop Residue Management (Shaffer and Larson, 1987) models. Pang et al. (1997a,b) used the CERES-Maize model to evaluate irrigation and N effects on NO_3^-–N leaching. Although leaching was not measured, the model predicted yield and N uptake, and the CERES model was used to evaluate how irrigation and fertilizer management practices affect NO_3^-–N leaching. NLEAP has also been reported to perform similarly to the LEACHM-N model (Wagenet and Hutson, 1989) in simulating NO_3^-–N leaching (Khakural and Robert,

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Abbreviations: BMPs, Best management practices; NLEAP, Nitrate Leaching and Economic Analysis Package; NLEFA, nitrate leaching equivalent of N fertilizer applied; NUE, N use efficiency; NUI, N uptake indices; RSN, residual soil nitrate; SLV, San Luis Valley.

1993). NLEAP simulations conducted by these and other authors were done with the 1.10 version, which was capable of only simulating the NO_3^-–N dynamics for the maximum rooting zone of the modeled crop (Shaffer et al., 1991, 1995; Follett et al., 1994). A new version of NLEAP, 1.20, was developed to simulate the RSN on the root zone of each crop and on a similar base line depth for cropping systems with different rooting depths (Delgado, 1998; Delgado et al., 2000, 1998a,b; Shaffer et al., 1998).

There is limited knowledge about how much N is lost by NO_3^-–N leaching below the root zone of these arid and semiarid irrigated potato–barley systems, and protocol on how to evaluate these systems has not been developed. There is a need to know what the balance is between the well water NO_3^-–N that is being added to the system with the irrigation water and the NO_3^-–N leaching from the system. If the NO_3^-–N that is being added to these systems with the irrigation water is greater than the NO_3^-–N translocated out of the system, then recommended BMPs are contributing to conserve water quality by contributing to a net NO_3^-–N recovery from the well water. If this balance is negative, then the system could potentially be contributing to environmental degradation, since we don't know if all the NO_3^-–N that is leached out of the system will eventually reach the underground well water (i.e., some may be lost by denitrification). Our objectives were to develop a protocol to evaluate the effects of recommended BMPs on NO_3^-–N leaching for these arid and semiarid irrigated potato–barley systems.

MATERIALS AND METHODS

Information about irrigation, N fertilizer application, planting, harvesting, cultivation, and other agricultural management practices were gathered on 14 commercial farmer fields that were in a potato–barley rotation. Recommended BMPs for nutrient and irrigation management in the SLV (Ristau, 1999) were used at these sites. Farmers applied N fertilizer rates on the basis of results from laboratory analysis of soil, plant tissue, and irrigation. Fertilizer N applications for potato were split into banded preplant and side-dressing applications and fertigations. There were no fall applications of N for spring planted crops.

During the growing season, the precipitation was measured at each site. Additional climatic data from the nearest weather station in the SLV (Center, CO) was also used. Potential evapotranspiration was calculated using the modified Jensen-Haise estimates (Follett et al., 1973; Jensen et al., 1990). Center pivot sprinklers were evaluated for efficiency, and during the growing season irrigation water samples were collected three times and analyzed for NO_3^-–N.

Soils were sampled in 0.3-m intervals to a depth of 0.9 m. For the initial and final soil samples at the whole field sites, we composited samples from 20 randomly located soil cores. Additional soil measurements for spring samples included water content, soil organic matter, pH, and cation exchange capacity. At 12 sites we measured available soil water at harvesting. Bulk densities were estimated from texture as described by USDA-SCS (1988). The soils used in these studies were (i) Gunbarrel: mixed, frigid Typic Psammaquents; (ii) Kerber: coarse-loamy, mixed, frigid Aquic Natrargids; (iv) McGinty: coarse-loamy, mixed, frigid Typic Calciorthids; (v) Norte: loamy-skeletal, mixed (calcareous), frigid Aquic Ustorthents; and (vi)) San Luis: fine-loamy over sandy or sandy-skeletal, mixed, frigid Aquic Natrargids. Additional chemical and physical properties of these soil types are described in Table 1.

Table 1. San Luis Valley soil types used for NLEAP simulations.

Soil series	Surface texture	Fields: Potato	Fields: Barley	SOM†	CoFV‡	pH§
				%	%	
Gunbarrel	Loamy sand	0	4	0.5–1.6	7–8	8.0–8.4
Kerber	Loamy sand	1	0	1.7	14	7.9
Norte	Gravelly sandy loam	1	2	1.0–1.5	13–23	7.9–8.0
McGinty	Sandy loam	3	0	1.6–1.7	4–6	8.0–8.2
San Luis	Sandy loam	2	1	1.0–1.7	3–11	7.8–8.0

† SOM = Soil organic matter for <2 mm soil fraction.
‡ CoFV = Coarse fragments by volume.
§ for <2 mm soil fraction.

Soil samples were air dried, and sieved through a 2-mm sieve. The weight of the coarse fragments was used to calculate the coarse fragment by volume (Delgado et al., 1999). Sieved samples were stored. For each sample, two extractions were conducted by weighing 20 g of soil, extracting with 100 mL of 2*M*KCl by shaking samples for 1 h, and the liquid fraction was filtered and saved for chemical analysis. Extracts were run for NO_3^-–N and NH_4^+–N with colorimetric analysis by a Technicon[1] autoanalyzer (Bran-Luebbe Analyzing Technologies, Elmsford, NY).

NLEAP 1.20 Inputs and Outputs

For the inputs, to conduct the simulations, we entered into the NLEAP model: crop planting and harvesting dates, N-, water-, and cultural-management inputs and timing, soil and climate information, and the expected yield. Additionally, we entered all N additions such as initial NO_3^-–N content of the soil, amount and type of N fertilizer added, amount of N in the irrigation water, crop residue mass, and its N content. We used the crop region.idx developed by Delgado et al. (1998b and 2000) and the N uptake indices (NUI) (N uptake per unit of yield). To develop these indices, plant samples were collected prior to farmers harvesting their fields. Plant samples were dried at 55°C for 2 d, ground, and analyzed for total C and N content by dry combustion with an automated C-N analyzer (Carlo Erba Strumentazione, Milan, Italy). At each of these fields we collected soil samples and truck loads of farmer's yields. Using the NUI and field yields, the model simulated the total N uptake at harvest. The mean root depth was measured by digging a hole at each site and measuring root depth.

NLEAP simulated RSN for three soil layers (root zone, bottom of the root zone to 0.9 m, and 0–0.9 m) within the profile of these cropping systems. Simulated NO_3^-–N values were compared with observed residual NO_3^-–N values. The model simulated NO_3^-–N leached from the rootzone of each crop and from the bottom of the 0.9 m soil profile. NLEAP simulations allowed the calculation of the net NO_3^-–N recovery from underground irrigation water. The net NO_3^-–N recovery from underground irrigation water was calculated as follows: (i) net NO_3^-–N recovery from underground irrigation water for the root zone = NO_3^-–N in the groundwater added as irrigation water to the field − NO_3^-–N leached from the root zone; and (ii) net NO_3^-–N recovery from underground

[1] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may be suitable.

Table 2. Mean fertilizer application, crop N content at harvest, and initial and residual soil NO_3^-–N (RSN) from 14 commercial sites of the San Luis Valley.

Crop	Total N fertilizer† applied	N fertilizer applied in irrigation‡	Soil NO_3^-–N at planting	Crop N content at harvest	RSN in Root zone	RSN 0–0.9 m (baseline depth)
	kg N ha^{-1}					
Potato	208***	65*	45*	173§	74***	145***
Barley	44	28	73	151	21	34

* Differences between potato and barley at $P < 0.05$.
*** Differences between potato and barley at $P < 0.001$.
† Total N fertilizer includes all dry and liquid N applications at preplanting, planting, sidedress, and through fertigations during the season.
‡ N fertilizer applied with irrigation.
§ Significant difference at $P < 0.14$.

irrigation water for the soil profile (0–0.9 m) = NO_3^-–N in the groundwater added as irrigation water to the field − NO_3^-–N leached from the soil profile (0–0.9 m). The model also estimated NUE as follows: NUE = [(total N content of crop at harvest/total N available in the 0–0.9 m soil profile) × 100]. Total N available included initial NO_3^-–N in the 0–0.9 m soil profile, added N fertilizer, N fertilizer added in irrigation, background N in irrigation water added to the field, and simulated N mineralization from soil and crop residue.

Statistical Analyses

Statistical analyses were performed using the SAS analysis of variance GLM procedure (SAS Institute, 1988). Our experimental unit was the commercial field. Although we recognize that no commercial field scenario is equal, we assumed that these 14 fields represented the effect of management practices for the potato and barley growing periods. We also assumed that with our protocol, by measuring site specific management, rain, irrigation, and other soil physical and chemical parameters, the model will simulate and account for a significant part of the variability from field to field. Correlations were made between predicted and observed available soil water using SAS REG (SAS Institute, 1988). The SAS REG procedure was also used for correlation between predicted and observed RSN. The intercept and slope were tested with SAS REG for differences from zero and one, respectively. We used the ANOVA to test for differences between the barley and potato growing periods.

RESULTS AND DISCUSSION

The amount of N fertilizer applied to the potato crop was 4.7 times more than that applied to malting barley (Table 2; $P < 0.001$). Potato also received a higher amount of N applied via irrigation water than the malting barley (Table 2; $P < 0.05$). When compared with the barley, observed RSN at harvesting was 3.5 times higher in the root zone of potato, and 4.3 times higher in the 0- to 0.9-m soil profile (Table 2; $P < 0.001$). The nitrate measured below the potato root zone was 71 kg NO_3^-–N ha^{-1}, and this was significantly greater than the 13 kg NO_3^-–N ha^{-1} below the barley root zone at harvest ($P < 0.001$). This shows a higher movement of NO_3^-–N below the root zone of the shallower-rooted potato crop ($P < 0.001$). The model was able to simulate the available soil water content and RSN in the root zone for the potato and barley growing periods (Fig. 1 and 2), below the root zone to the baseline of 0.9 m (Fig. 3), and for the whole profile, 0 to 0.9 m (Fig. 4). The intercept and slope were not significantly different from zero and one, respectively, for the respective potato and barley growing periods or the whole data set (potato and barley).

Although small grains usually have a rooting depth to 1.00 m, and barley roots can reach depths of up to 1.80 to 2.10 m, the average root depth measured for malting barley in our studies (0.61 m) in the SLV, were slightly shallower than those reported by Murray (1993) for barley grown in Idaho (0.61 to 0.91 m). This shows the importance of collecting site specific information (Delgado et al., 1998a). Although the mean root zone depth for potato and barley were 0.40 and 0.61 m, respectively, we conducted the simulations to a baseline soil depth of 0 to 0.90 m.

Barley evapotranspiration was higher, and the amount of irrigation water used was 9% more than that used on the potato (Table 3, $P < 0.05$). NLEAP 1.20 simulated the effect of BMPs on available soil water for the root zone of potato and barley (Fig. 1). The NO_3^-–N ha^{-1} added in irrigation water was higher for barley (54 kg NO_3^-–N ha^{-1}) than for potato (32 kg NO_3^-–N ha^{-1}) ($P < 0.01$). This difference was because of differences in irrigation water inputs.

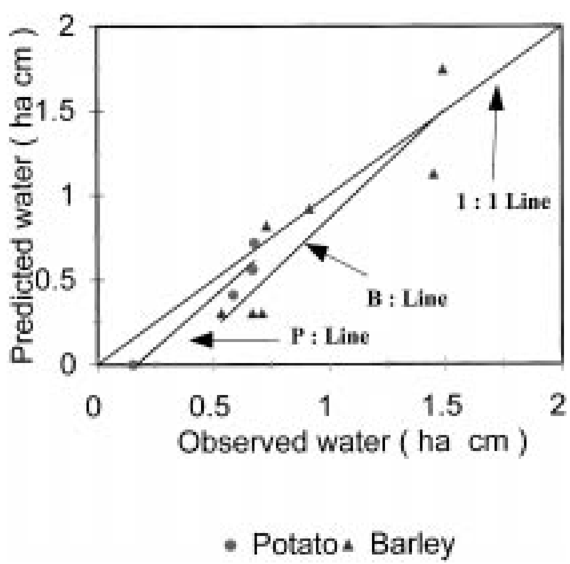

Fig. 1. Observed and NLEAP-predicted available soil water in the root zone at harvest for potato (P) and barley (B) grown in the San Luis Valley. Regression line for the barley growing period (Line B) is $y = -0.44 + 1.3x$ ($r^2 = 0.81$, significant at $P < 0.05$). The potato growing period has an equation as follows (Line P): $y = -0.20 + 1.2x$ ($r^2 = 0.93$, significant at $P < 0.01$). The regression equation for the whole data set P and B (line not shown) is $y = -0.27 + 1.2x$ ($r^2 = 0.82$, significant at $P < 0.01$).

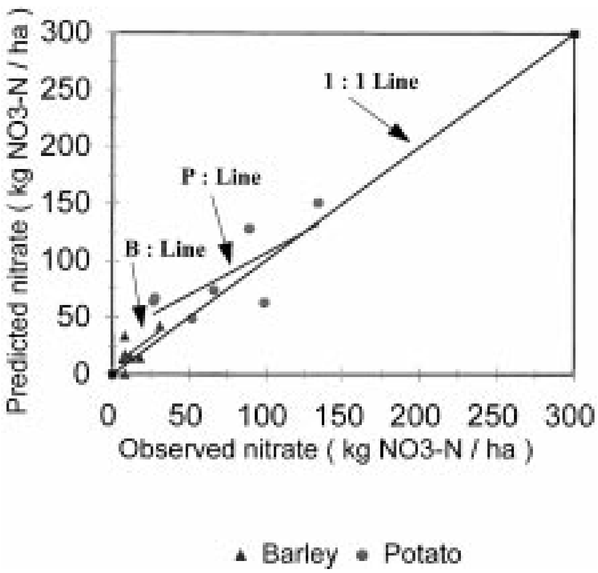

Fig. 2. Observed and NLEAP-predicted residual soil NO_3^-–N (RSN) in the root zone of potato (P) and barley (B) grown in the San Luis Valley. Regression line for the barley growing period (Line B) is $y = 6.19 + 0.72x$ ($r^2 = 0.70$, significant at $P < 0.01$). The potato growing period has an equation as follows (Line P): $y = 8.49 + 0.82x$ ($r^2 = 0.43$, significant at $P < 0.05$). The regression equation for the whole data set P and B (line not shown) is $y = 4.7 + 0.86x$ ($r^2 = 0.71$, significant at $P < 0.001$).

Simulated NO_3^-–N losses to leaching from the root zone of potato (94 kg NO_3^-–N ha^{-1}) were three times higher than for barley (34 kg NO_3^-–N ha^{-1}). The net NO_3^-–N recovery from underground irrigation water was −63 and −14 kg NO_3^-–N ha^{-1} below the root zone and below the 0- to 0.9-m depth, respectively, during the potato growing period (Table 4). These losses are

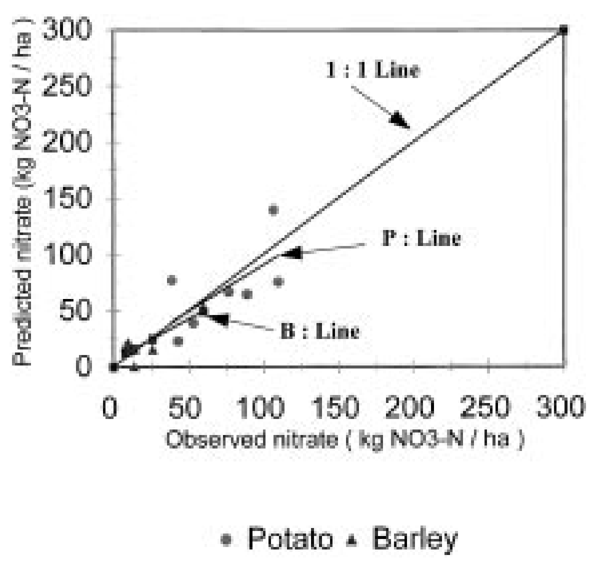

Fig. 3. Observed and NLEAP-predicted residual soil NO_3^-–N (RSN) in the bottom of the root depth to 0.9 m soil depth of potato (P) and barley (B) grown in the San Luis Valley. Regression line for the barley growing period (Line B) is $y = 7.15 + 0.98x$ ($r^2 = 0.39$, significant at $P < 0.13$). The potato growing period has an equation as follows (Line P): $y = 33.15 + 0.73x$ ($r^2 = 0.56$, significant at $P < 0.01$). The regression equation for the whole data set P and B (line not shown) is $y = 12.5 + 0.95x$ ($r^2 = 0.78$, significant at $P < 0.001$).

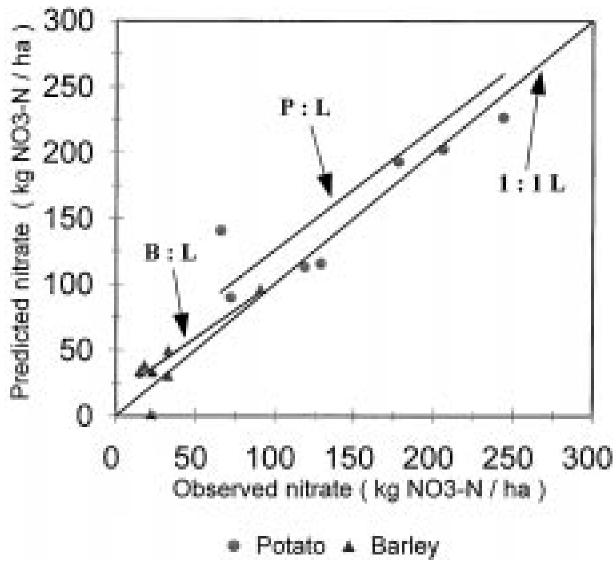

Fig. 4. Observed and NLEAP-predicted residual soil NO_3^-–N (RSN) in the 0- to 0.9-m soil depth profile of potato (P) and barley (B) grown in the San Luis Valley. Regression line for the barley growing period (Line B) is $y = 9.55 + 0.94x$ ($r^2 = 0.75$, significant at $P < 0.01$). The potato growing period has an equation as follows (Line P): $y = 53.8 + 0.70x$ ($r^2 = 0.79$, significant at $P < 0.01$). The regression equation for the whole data set P and B (line not shown) is $y = 17.7 + 0.90x$ ($r^2 = 0.90$, significant at $P < 0.001$).

reported as potential contributions since we don't know if all the NO_3^-–N that is leached out of the system will eventually reach the underground well water (e.g., some may be lost by denitrification).

The malting barley net NO_3^-–N recovery from underground irrigation water was 20 kg NO_3^-–N ha^{-1} at this similar 0- to 0.9-m depth. The inclusion of malting barley in rotation with potato actually increases the net NO_3^-–N recovery from underground irrigation water for the potato–barley rotation to 3 kg NO_3^-–N ha^{-1}. Although the NO_3^-–N leaching from the potato root zone during the potato growing period was 94 kg NO_3^-–N ha^{-1}, when we evaluated the potato–barley rotation, the systems net NO_3^-–N recovery from underground irrigation water was 3 kg NO_3^-–N ha^{-1} yr^{-1}. This shows that BMPs that include a deeply rooted crop and one that keeps RSN available for that deep rooted crop increases the NUE of the system and reduces the NO_3^-–N losses (Table 4).

By using these BMPs and accounting for high initial RSN at planting in the malting barley system, and applying adequate (lower) N fertilizer, the quality of grain was conserved (low protein content) and high yields were achieved (7000 kg ha^{-1} at 12% moisture). Potato yields average 40 Mg ha^{-1} (at 80% moisture).

Table 3. Total irrigation, precipitation, and the simulated evapotranspiration and water leachate from the bottom of the root zone.

Crop	Irrigation	Precipitation	Evapotranspiration	Leachate
	ha cm			
Potato	14.4†	5.3‡	17.3§	2.6‡
Barley	16.7	5.9	19.0	2.8

† Difference between potato and barley at $P < 0.18$.
‡ No significant differences between potato and barley.
§ Difference between potato and barley at $P < 0.11$.

Table 4. NO_3^-–N balance and use efficiency for potato and barley growing periods of a potato-barley rotation. The background NO_3^-–N added with the well irrigation water during the growing period was accounted for. The NO_3^-–N leaching from the root zone and soil profile was used to calculate the net well water NO_3^-–N recovery. The N use efficiency in the system is also presented.

Crop	Background NO_3^-–N in irrigation	NO_3^-–N leached from root zone	NO_3^-–N leached from 0.9 m depth	Net recovery† of NO_3^-–N root zone	Net recovery‡ of NO_3^-–N 0.9 m depth	N use efficiency in the system
	kg NO_3N ha^{-1}					%
Potato	32**	94*	45§	−63**	−14¶	47**
Barley	54	34	34	19	20	70

* Difference between potato and barley at $P < 0.05$.
** Difference between potato and barley at $P < 0.01$.
† Net recovery NO_3^-–$N_{root\ zone}$ = Irrigation water NO_3^-–N − Root zone NO_3^-–$N_{leaching}$.
‡ Net recovery NO_3^-–$N_{soil\ profile}$ = Irrigation water NO_3^-–N − Soil Profile (0.91 m depth) NO_3^-–$N_{leaching}$.
§ No significant differences between potato and barley.
¶ Significant difference at $P < 0.12$.

These results show that with BMPs for irrigation, not all the NO_3^-–N that is leaving the root zone of potato (0–0.4 m) leaves the root zone of the following, deeper rooted malting barley (0.61 m). This keeps losses of NO_3^-–N to a minimum and gives the opportunity to scavenge RSN to the next, deeper rooted crop.

CONCLUSIONS

We used NLEAP 1.20 to simulate the NO_3^-–N dynamics in and below the root zone and to conduct a NO_3^-–N balance between inputs and outputs of NO_3^-–N in the rotation. Although simulated NO_3^-–N leaching from the shallower rooted crop was equivalent to 45% of the N fertilizer applied (NLEFA), when we accounted for the background NO_3^-–N in irrigation water, the NLEFA was only 30%.

Best management practices can contribute to increasing the net NO_3^-–N recovery from underground irrigation water, an equivalent of 2% of the N fertilizer applied. Simulating the NO_3^-–N dynamics in a potato–barley system shows that NLEFA was −2% per year. The malting barley period is a significant improvement in management that has the potential to increase the system's N use across the potato period by increasing the mean efficiency of the barley-potato period to ≈60%. Our results agreed with other researchers who reported that NO_3^-–N leaching losses below the root zone in irrigated sandy soils can be kept to a minimum with proper water and fertilizer N management practices (Smika et al., 1977; Hergert, 1986; Westerman et al., 1988; Schepers et al., 1995; Thompson and Doerge, 1996a,b).

The previous NLEAP 1.10 version was able to conduct its simulations for only the root zone of the simulated crop, and could not be used to evaluate the effects of BMPs on RSN for cropping systems that have variable rooting depths. The new NLEAP 1.20 version allows us to simulate how much NO_3^-–N is leaching from both systems on a similar baseline. Although each field needs to be evaluated individually, extrapolating our results suggests that over the 24 300 and 28 350 ha for potato and barley, respectively, planted in the SLV, 567 000 kg NO_3^-–N yr^{-1} are recovered during the malting barley period. This is equivalent to the mean N fertilizer needed for 2700 ha of potato or ≈50 center-pivot sprinkler irrigation sites. These new 1.20 capabilities show that NLEAP 1.20 can be used as a protocol in other potato-malting barley areas of the USA to evaluate BMPs and their impacts on N budgets and transport of NO_3^-–N in and out of the root zone.

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